FACTORS AFFECTING THE EFFICIENCY OF WORK OF THE HORIZONTAL EARTH-AIR HEAT EXCHANGER IN GEOTHERMAL VENTILATION SYSTEM

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Abstract. To save energy in mechanical ventilation systems, it is advisable to use earth-air heat exchangers. They are intended for the transfer of low-potential soil heat to the air entering the ventilation system. The efficiency of heat exchange between soil and air depends on many factors. Moreover, some factors significantly affect the heat transfer process, and some can be neglected. This article identifies all factors that affect the performance of a horizontal earth-air heat exchanger. It is determined which factors depend on the location of soil heat exchangers, and, accordingly, are permanent for the concrete the terrain. There are factors that can vary depending on the task of designing the object. The basic parameters are determined, the change of which will allow to increase the heat exchange between soil and air in the heat exchanger, in particular, the speed of air movement and the diameter of the pipe of the heat exchanger. In addition, the intensification of heat transfer is carried out by the turbulence of air flow in the soil heat exchanger.

Keywords: geothermal ventilation system, thermophysical characteristic, geometrical parameter, horizontal earth-air heat exchanger, convective heat transfer coefficient.

Introduction

The main direction of the energy policy of Ukraine is the rational use of fuel and energy resources in all sectors of the national economy. In the housing and utilities sector more than 35% of all energy resources are spent. Thus, the introduction of the concept of passive construction during the reconstruction of existing and designing innovative houses will save traditional energy resources. As it is known, the main requirements for the construction of passive houses are the high level of thermal insulation and tightness of the external fencings of the building, the lack of thermal bridges in the buildings and the use of mechanical tidal and exhaust ventilation ventilation with heat recuperator. (Passive House Institute, 2016)

The values of the regulatory heat transfer resistance of the buildings' external fencings in Ukraine are increasing periodically. Over the past 20 years, the heat transfer resistance of external fencing has almost doubled (Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, 2017) and a significant number of energy-saving window designs have been presented in the Ukrainian market. However, the requirements for designing ventilation systems in residential and public buildings over the past 25 years have not changed much. Only a natural exhaust ventilation system from the kitchen, toilet and bathroom is obligatory in residential buildings [State committee of Ukraine construction and architecture, 2005]. Although in Ukraine there is a normative document DSTU B EN 15251:2011 [4], which contains requirements for a tidal ventilation system in residential premises, yet the installation of mechanical ventilation in Ukraine is carried out, if necessary, only in high-rise buildings. (Savchenko et al., 2017)] Installation of tidal and exhaust mechanical ventilation system with the presence of a heat exchanger in Ukraine is carried out for large shopping and office centres, mainly when projects are financed by foreign firms. Installation of a mechanical tidal and exhaust ventilation system in residential buildings will allow maintaining the permissible meteorological and sanitary-hygienic parameters of air in the room, such as air humidity, CO_2 concentration, odour levels at a given level. (Kapalo et al., 2014) In addition, when using mechanical ventilation system in residential buildings, there is no reciprocation in the ventilation ducts, thus fungus and mold can be found in the corners of the premises and on the slopes of the windows. As it is known, it is advisable to use air-to-air heat exchangers for the use of heat of exhaust air and earth-air heat exchangers for the use of low-potential heat of surface layers of ground in order to save energy in mechanical ventilation systems.

The purpose and objectives of the study

Identification of the major factors that influence the process of heat transfer from ground to air in the heat exchanger, and accordingly on the efficiency of the operation of a horizontal earth-air heat exchanger in geothermal ventilation systems.

Analysis of Existing Data

Earth-air heat exchangers are an element of the system of geothermal ventilation. They are laid underground at a depth of 2-5m, where the temperature of the soil does not change significantly during the year and is 2-10°C. They are intended for heat exchange between the air in the heat exchanger and the ground. (Filatov and Volodin, 2011) In the cold period of the year, the cold air outside passing through the pipes of the heat exchanger takes heat from the ground through the walls of the pipes and heats up. In the warm period of the year, on the contrary, when passing through the earth-air heat exchanger hot external air gives its heat to the soil and cools it. Therefore, in the warm period of the year, earth-air heat exchangers are expedient to use for preliminary cooling of external air entering the ventilation system. Depending on laying in an array of ground, earth-air heat exchangers are vertical and horizontal. Horizontal heat exchangers, in turn, are channel (tubular), non-channel and membrane-free. (Zhelykh et al., 2016)

The schematic diagram of the geothermal ventilation system is shown in Fig.1. The geothermal ventilation system works as follows: the external air required for ventilation of the building through the air intake unit 1 enters the earth-air heat exchangers 2, in which heat exchange between the outside air and the ground occurs. In the cold period of the year, after the earth-air heat exchanger air is fed to the recuperator 3, which heats it using the heat of the exhaust air. Fresh air in the room is delivered by means of tidal air ducts with air distributors 4, and the removal of air from the premises is effected by air ducts with air intake devices 5. Having left its heat in the recuperator, the exhaust air is extracted by the air extract unit 6.

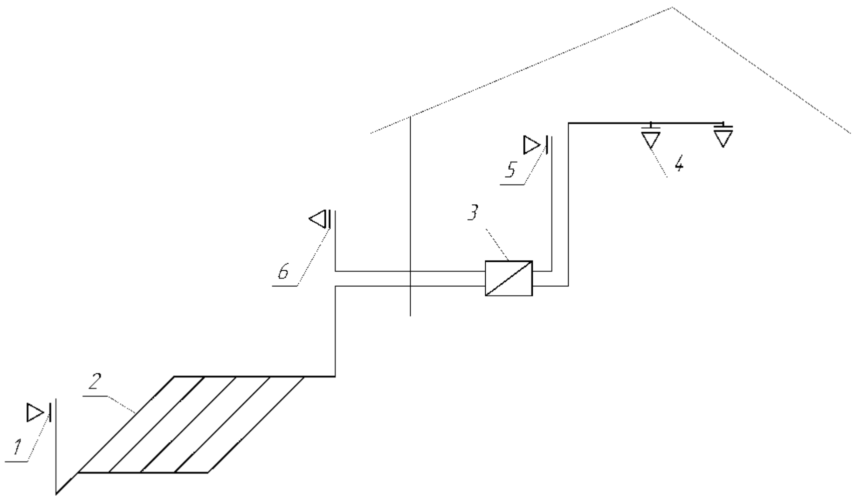

Figure 1. Schematic diagram of the geothermal ventilation
1 – air intake unit, 2 - horizontal earth-air heat exchangers, 3 - recuperator,
4 – air distributor, 5 – air intake device, 6 - air extract unit

The main disadvantage of horizontal heat exchangers is the large area of the site for their laying, which for channel (pipe) heat exchangers depends on the total length of the pipe of heat exchanger. Therefore, the main task when designing horizontal earth-air heat exchangers is to increase the amount of heat that is transmitted from ground to air in the heat exchanger. This task can be accomplished by establishing all the factors that influence the work of the soil heat exchanger and analyzing their impact on the efficiency of the soil heat exchanger.

The Main Material

The factors affecting the process of heat exchange between a ground and external tidal air include (Bisoniya, T. S., 2015):

- thermophysical characteristics of the soil: temperature, coefficient of thermal conductivity, density, specific heat, coefficient of thermal conductivity;
- geometrical parameters of the heat exchanger: the length and diameter of the heat exchanger pipes, the thickness of the wall of the heat exchanger pipe, the step and the layout of the heat exchanger;
- thermophysical characteristics of the heat exchanger: heat exchanger material,

coefficients of thermal conductivity and thermal diffusivity;
- thermophysical properties of the air moving in the heat exchanger: air temperature at the inlet and outlet of the heat exchanger, density, thermal conductivity coefficient, convective heat transfer coefficients on the inner and outer surfaces of the heat exchanger pipe, air flow velocity, volume air flow, cause of air movement (natural or forced convection), flow mode (laminar or turbulent).

All factors that affect the operation of the soil heat exchanger can be divided into three groups.

The first group includes factors that are known for the terrain in which it is planned to build an earth-air heat exchanger. Although they affect the process of heat exchange between ground and air, it is not possible to change them in the concrete terrain. These factors influence the thermophysical properties of the soil and some thermophysical properties of the outside air.

It is obvious that the thermophysical properties of ground depend on the type of ground [10 (Zhelykh et al., 2015) and can be described by one value, which is called the coefficient of thermal diffusivity a. It determines the rate of change the ground temperatures due to the absorption or return of heat coming from the bowels of the Earth, m^2/s, and is determined by the formula:

$$a = \frac{\lambda}{\rho \cdot C} \qquad (1)$$

where λ - coefficient thermal conductivity of the ground, W/(m·K), ρ - density of ground, kg/m^3, C – specific heat of the soil, kJ/(kg·K).

For soil types that prevail in Ukraine, the values of the coefficients of thermal diffusivity are shown in Table 1.

Table 1. The coefficients of thermal diffusivity of ground

The types of soil	a, m^2/s
Alumina	0,001151-0,001103
Limestone	0,000697
Dry sand	0,000275
Sand with humidity of 10 %	0,000808
Sand with humidity of 20 %	0,001108
Sandy soil	0,000703-0,00175
Soil dry	0,00034-0,000298
Soil compacted	0,000656-0,000175

The temperature of the ground depending on the depth of the laying of the heat exchanger and the day of the year is determined by the known formula:

$$T_s = \overline{T_s} + A \cdot e^{-x\sqrt{\frac{\pi}{365a}}} \cdot \sin\left(\frac{2\pi(t - t_o)}{365} - x\sqrt{\frac{\pi}{365a}} - \frac{\pi}{2}\right) \qquad (2)$$

where x - depth of ground, m; t - day of the year; $\overline{T_s}$ - the annual average surface temperature of the soil taken equals to an annual average outdoor air temperature for the selected region, °C; A - annual amplitude fluctuation of the surface temperature of the ground, °C, a - coefficients of thermal diffusivity of the ground, m^2/s; t_o - time lag (in days) from a random initial date of the emergence of the minimum temperature in year.

There are no recommendations on selecting the outside air temperature t_{out} in the designing of earth-air heat exchangers in Ukrainian normative documents. In (Bisoniya, 2015) it is stated that the temperature of the outside air is taken as the average annual temperature of the outside air in the terrain. In the computer program of the calculation of earth-air heat exchangers from Rehau the temperature of the outside air is taken as the temperature of the outside air in the five coldest days of the given terrain.

The thermophysical characteristics of the external and air depend on the temperature of the air, including density, coefficient of thermal conductivity and coefficients of viscosity. Thus, the density and coefficient of thermal conductivity of air at atmospheric pressure depending on its temperature can be taken from Table 2.

The second group includes factors that depend on the task of designing the object. Such factors include the volume of air that requires preparation for the geothermal ventilation system and the temperature of the air at the outlet of the earth-air heat exchanger. The volume of air flow, m^3/h, is conveniently determined by the air changes per hour:

$$L = k \cdot V \qquad (3)$$

where k – ach air changes per hour depends on the category of indoor microclimate of the premises. In accordance with (Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, 2012) for category I k = 0.7, for category II k = 0.6, for category III k = 0.5.V – volume of premises in which it is necessary to supply fresh air, m^3.

Table 2. The density and the coefficient of thermal conductivity of air

t_{out}, °C	ρ, kg/m^3	λ, W/(m·K),
–53	1,604	0,01983
–23	1,412	0,02207
–3	1,307	0,02348
0,1	1,293	0,02370
7	1,261	0,02417
17	1,217	0,02485
27	1,177	0,02553
37	1,139	0,02621

The second group includes factors that depend on the task of designing the object. Such factors include the volume of air that needs to be prepared for the geothermal ventilation system and the temperature of the air at the outlet of the earth-air heat exchanger. The volume of air flow, m^3/h, is conveniently determined by the air change rate:

$$L = k \cdot V \quad (3)$$

where k –air changes per hour depends on the category of indoor microclimate of the premises. In accordance with (Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, 2012) for category I k = 0.7, for category II k = 0.6, for category III k = 0.5.V – volume of premises, in which it is necessary to supply fresh air, m^3.

The minimum outside air temperature at the outlet of the earth-air heat exchanger t_{in} is taken from the condition of preventing the icing of the recuperator in the mechanical ventilation system for the second heating of the outside air.

All other factors belong to the third group, their change affects the amount of heat that is transmitted from ground to air in the heat exchanger. This group includes the thermophysical properties of the heat exchanger tube, the geometrical parameters of the heat exchanger and the thermophysical properties of the air in the heat-exchanger.

The thermophysical properties of the heat exchanger tube depend on the material from which it is made. As materials for pipes of earth-air heat exchangers, polymer materials, concrete and steel are used. The authors (Sobti and Singh, 2015) consider steel as the most effective material due to its high coefficient of thermal conductivity (Table 3).

Table 3. Coefficient of thermal conductivity of materials for earth-air heat exchangers

Material	λ, W/(m·K)
Steel	52
Concrete	1,75
Polypropylene	0,23

However, steel pipes in the ground can corrode easily, which leads to the formation of cracks in the wall of the heat exchanger pipe and the penetration of groundwater into the pipe. It is expedient to use steel pipes only in a dry ground, but the thermal conductivity and accumulation capacity of such a ground are low. The main disadvantage of concrete pipes is the high coefficient of roughness of their inner surface. (Rehau UA, 2015) Such a surface becomes a potential incubator for the reproduction of microorganisms, which then, together with air, will be supplied by the system of ventilation in the room. In addition, concrete pipes have a significant mass, are easily damaged, and their installation is rather complicated. Pipes of polymeric materials have a number of advantages, including a smooth inner surface and a small mass, the material is resistant to corrosion, and the installation of the heat exchanger is easy.

The main thermophysical characteristic, which affects the amount of heat that is transmitted from soil to air in the heat exchanger, is the convective heat transfer coefficient. The convective heat transfer coefficient from the inner surface of the heat exchanger pipe, W/(m^2·K), is defined as:

$$\alpha_{in} = \frac{Nu \cdot \lambda_{air}}{d_{in}} \quad (4)$$

where Nu - Nusselt criterion, λ_{air} – the coefficient of thermal conductivity of air, which is transported by the heat exchanger, W/(m·K), d_{in} - internal diameter of the pipe of the heat exchanger, m.

The Nusselt criterion, in turn, depends on many indicators, in particular, the method of inducing air movement (natural or forced convection), air velocity, flow regime (laminar or turbulent), and also the thermophysical parameters of air (coefficient of dynamic viscosity, specific heat, density). These factors are taken into account with the help of dimensionless Reynolds Re, Grashof Gr and Prandtl Pr criteria:

$$Nu = f(Re, Gr, Pr), \quad (5)$$

The Reynolds criterion is used to determine the dynamic similarity of various experimental flow studies and to characterize the flow mode. Grashof's criterion determines the efficiency of the lifting force, which causes the free convection motion of a viscous substance. The Prandtl criterion defines the similarity of the fields of velocity and temperature in the flow and is a measure of the ratio of the intensity of the transfer of momentum to internal friction and the intensity of the energy transfer of the heat conductivity in the flow of matter. They can be determined by the following dependencies:

$$Re = \frac{\rho \cdot v \cdot d_{in}}{\mu} = \frac{v \cdot d_{in}}{\nu}, \quad (6)$$

$$Gr = \frac{g \cdot d^3 \cdot \beta (t_{wall} - t_{out})}{\nu^2}, \quad (7)$$

$$Pr = \frac{\nu}{a}, \quad (8)$$

where ρ - air density, kg/m^3; v – speed of air movement in the pipe of the heat exchanger, m/s; d_{in} – internal diameter of the pipe of the heat exchanger, m; μ - coefficient of dynamic viscosity, Pa·s; ν – coefficient of kinematic viscosity, m²/s; g – acceleration of free fall, g = 9,81 m/s^2; t_{wall} – temperature on the inner surface of the pipe wall of the heat exchanger, °C; t_{out} – the temperature of the external air moving in the heat exchanger, °C; β – the temperature coefficient of volumetric expansion of external air, 1/K, for gases can be defined as $\beta = \frac{1}{273 + t_{out}}$; a – coefficient of thermal diffusivity, m²/s.

As seen from the formula (4), the higher the value of the Nusselt criterion and the coefficient of thermal conductivity and the smaller values of the diameter of the pipeline, the greater the value of the convective heat transfer coefficient from the wall of the heat exchanger to the air. Since the coefficient of thermal conductivity of the air in the temperature range that is characteristic of the operation of the soil heat exchanger does not change significantly, in order to increase the coefficient of heat transfer, it is necessary to increase the Nusselt criterion and reduce the diameter of the pipeline. The Nusselt criterion can be reduced by increasing the speed and turbulence of the air flow in the heat exchanger pipe.

The geometric parameters of the heat exchanger depend on the thermophysical properties of the outside air and the soil in which the soil heat exchanger is located. Only knowing these parameters, the length and diameter of the pipes of the heat exchanger can be determined. The scheme of laying the earth-air heat exchanger depends on the required air exchange in the ventilation system. Three schemes for laying a heat exchanger such as Domestic Loop Layout, Tichelmann Pipe Layout and Coil Pipe Layout are known so far (Fig.2).

Domestic Loop Layout is used for buildings, where the required air exchange does not exceed 250 m^3/h. The other two circuits are used for houses that require ventilation air. Coil Pipe Layout has larger pressure losses when passing the air through the heat exchanger than in the Tichelmann Pipe Layout, thus it requires a more powerful fan to stimulate the movement of air. Domestic Loop Layout is used for buildings, where the required air exchange does not exceed 250 m^3/h. The other two circuits are used for homes that require more quantity ventilation air. Coil Pipe Layout has larger pressure losses when passing the air through the heat exchanger than in the Tichelmann Pipe Layout, therefore it requires a more powerful fan to stimulate the movement of air.

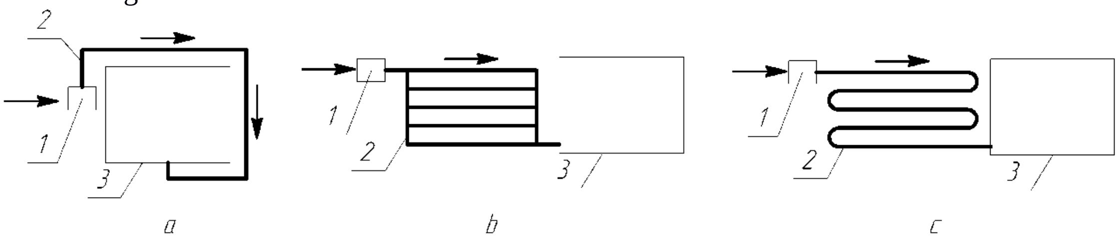

Figure 2. The scheme of laying the earth-air heat exchangers in geothermal ventilation
a - Domestic Loop Layout, b - Tichelmann Pipe Layout, c - Coil Pipe Layout,
1 – air intake unit, 2 – earth-air heat exchanger, 3 – building.

The step of the heat exchanger tubes is taken for the possibility of maximizing the heat transfer between the ground and the heat exchanger pipe, to avoid premature exhaustion of the ground mass between the two neighbouring pipes of the heat exchanger. Firm Rehau recommends the step of laying pipes 1 m.

Conclusions

All factors that affect the efficiency of the soil heat exchanger are established. It is determined which factors depend on the construction place, and which can be changed to increase the efficiency of the soil heat exchanger. It was established that the main indicators that will increase the heat exchange between soil and air in the soil heat exchanger are the speed of air movement and the diameter of the pipe of the heat exchanger.

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